Theoretical Neuroscience (Applied Physics 293)

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All higher level cognitive functions, like perception, attention, learning, decision making, and memory, emerge from networks of neurons coupled to each other through synapses. Although we understand a great deal now about how single neurons transform inputs to outputs, and how single plastic synapses change their efficacies in an activity dependent manner, the question of how many such relatively simple biophysical units interact with each other to give rise to complex higher level cognitive phenomena remains one of the most striking conundrums in modern neuroscience. An essential component of progress on this question is the generation of testable, quantitative theories of information processing, collective dynamics, and plasticity induced structural reorganization in neuronal networks. The goal of this course is to introduce and survey such theories (many of which are inspired from physics) that provide deep conceptual insights into how we might connect biophysics to cognition. Along the way we will emphasize the development of mathematical skills necessary to analyze complex neural systems. We will attempt to make this course self-contained so that it is of interest both to biologists who wish to learn theory as well as theoretically minded students (i.e. physicists, mathematicians, engineers, etc..) who wish to learn the applications of theory to neurobiology.

Syllabus:

Neural Coding, Perception and Attention

Basic models of single neurons
Neuronal population coding of external stimuli
Theory of Fisher information and coding performance
Impact of neuronal correlations and heterogeneity on coding
Impact of attention on single neurons, population codes and perception

Network Plasticity and Learning

Synaptic biophysics
Analysis of unsupervised learning rules
The acquisition of stimulus specificity (ocular dominance and orientation selectivity)
How plastic networks can perform statistical analysis (PCA, ICA, clustering)
Analysis of supervised learning rules
Theory of learning and generalization in feedforward networks

Network Dynamics, Decision Making and Memory

Analysis of dynamics and computation in feedforward and recurrent networks
Theory of neural integration and decision making
Mean field theories of network dynamics and correlations
Analogies to statistical physics
Principles of associative memory in attractor networks
Theories of memory capacity in neuronal networks